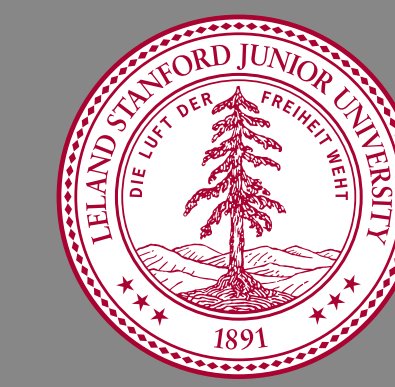# Algorithmic Foundations for Real-Time and Dependable Spacecraft Motion Planning

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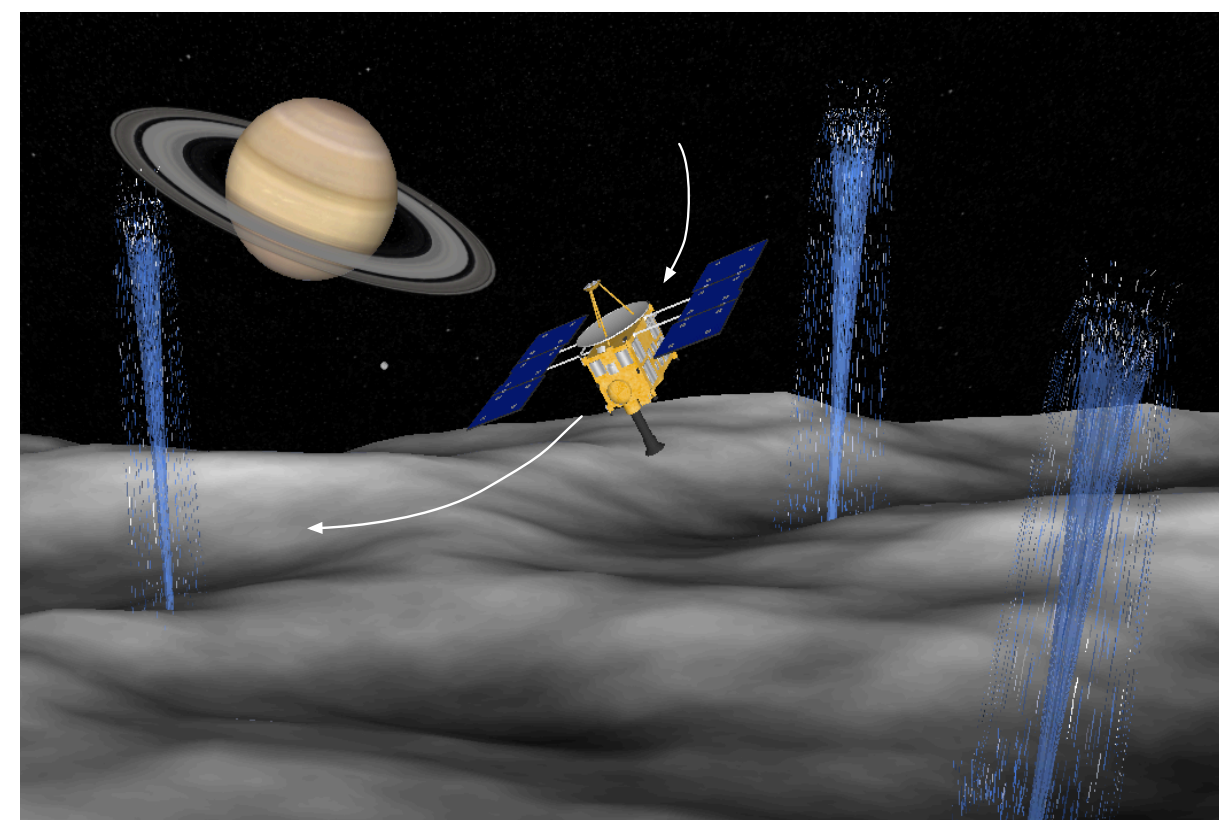
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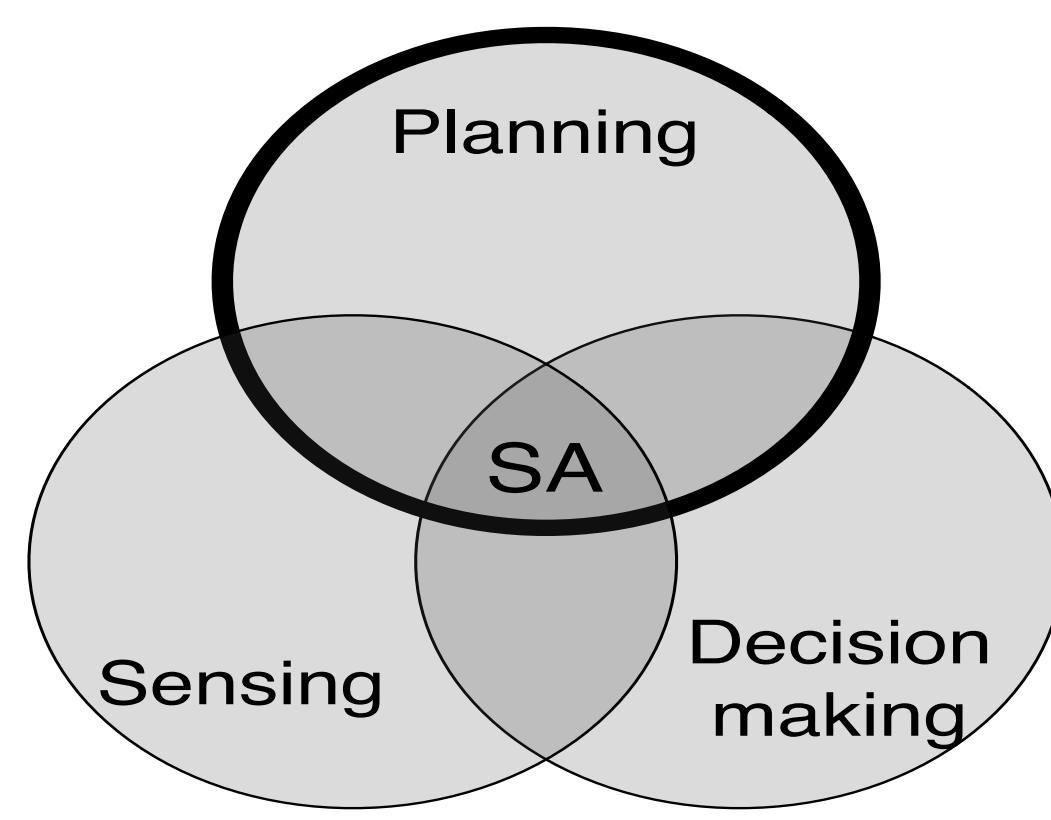
Objectives

Devise real-time, efficient and dependable algorithms for **spacecraft autonomous maneuvering**, with a focus on dynamic and cluttered environments

(a) Autonomous planning in proximity of outgassing material on the surface of Enceladus

(b) The focus of this proposal is on online planning of spacecraft trajectories, and its interplay with sensing and decision-making
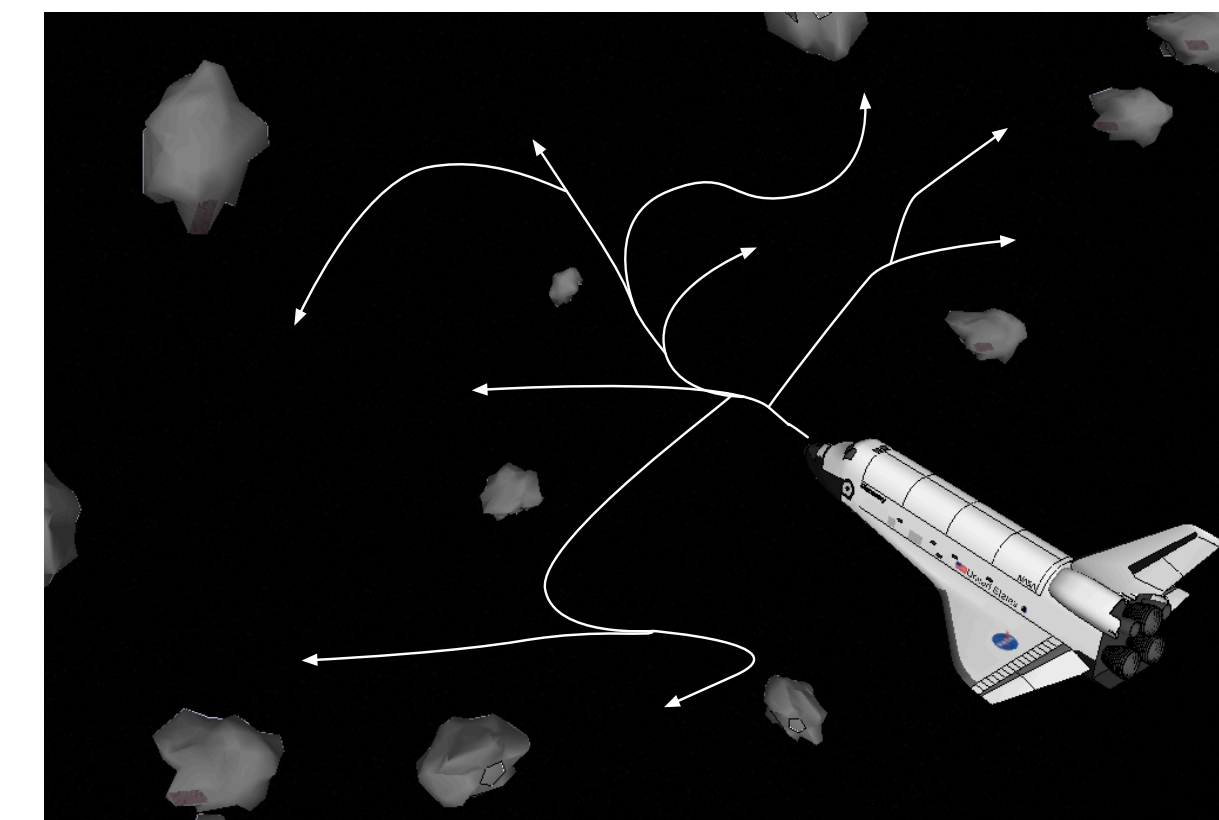
(c) Planning in dynamic and cluttered environments requires fast re-planning and anytime computation, e.g., through tree data structures

Figure 1 Autonomous spacecraft navigation and maneuvering is an enabling factor for a wide range of missions, ranging from on-orbit satellite servicing to operations in proximity of outgassing bodies (Figure 1(a)). Generally speaking, spacecraft autonomy (SA) entails reliable environmental sensing, autonomous high-level decision making, and online planning of trajectories (see Figure 1(b)). In this effort we will focus on this last aspect, by devising algorithms for the *online* planning of trajectories in dynamic and cluttered environments (e.g., algorithms that construct in real-time *trees* of feasible trajectories, which are incrementally improved if more deliberation time is allowed –a feature known as anytime computation–, Figure 1(c))

Expected significance

- Traditional approaches are mainly geared toward static and uncluttered environments

- On the other hand, many future NASA missions will require autonomous maneuvering in dynamic and cluttered environments (e.g., due to debris or outgassing activity)

- Key novelty: leverage recent algorithmic advances in the field of robotic motion planning for autonomous driving to spacecraft control

- Key technological contribution: tailor anytime, incremental robotic planning algorithms to the solution of the "spacecraft motion planning problem"

- Key benefit to NASA:
  - Enable servicing missions in Near-Earth orbits
  - Enable several of the missions recommended by the Planetary Science Decadal Survey 2013-2022 (e.g., exploration of Saturnian and Uranian systems)

Approach and methods

Approach:

- Incremental sampling-based algorithms (RDTs)
  - **Anytime**: *trees* of feasible trajectories, incrementally improved if more deliberation time is allowed
  - **Safe**: safety constraints encoded within the planning process
  - **Sampling-based**: scale to high-dimensional spaces, coupled geometric and differential planning

- Three research pillars:
  - **Pillar 1**: theoretical and algorithmic advances to allow implementation on spacecraft-like hardware (with tight computational constraints)
  - **Pillar 2**: integration into spacecraft autonomy module
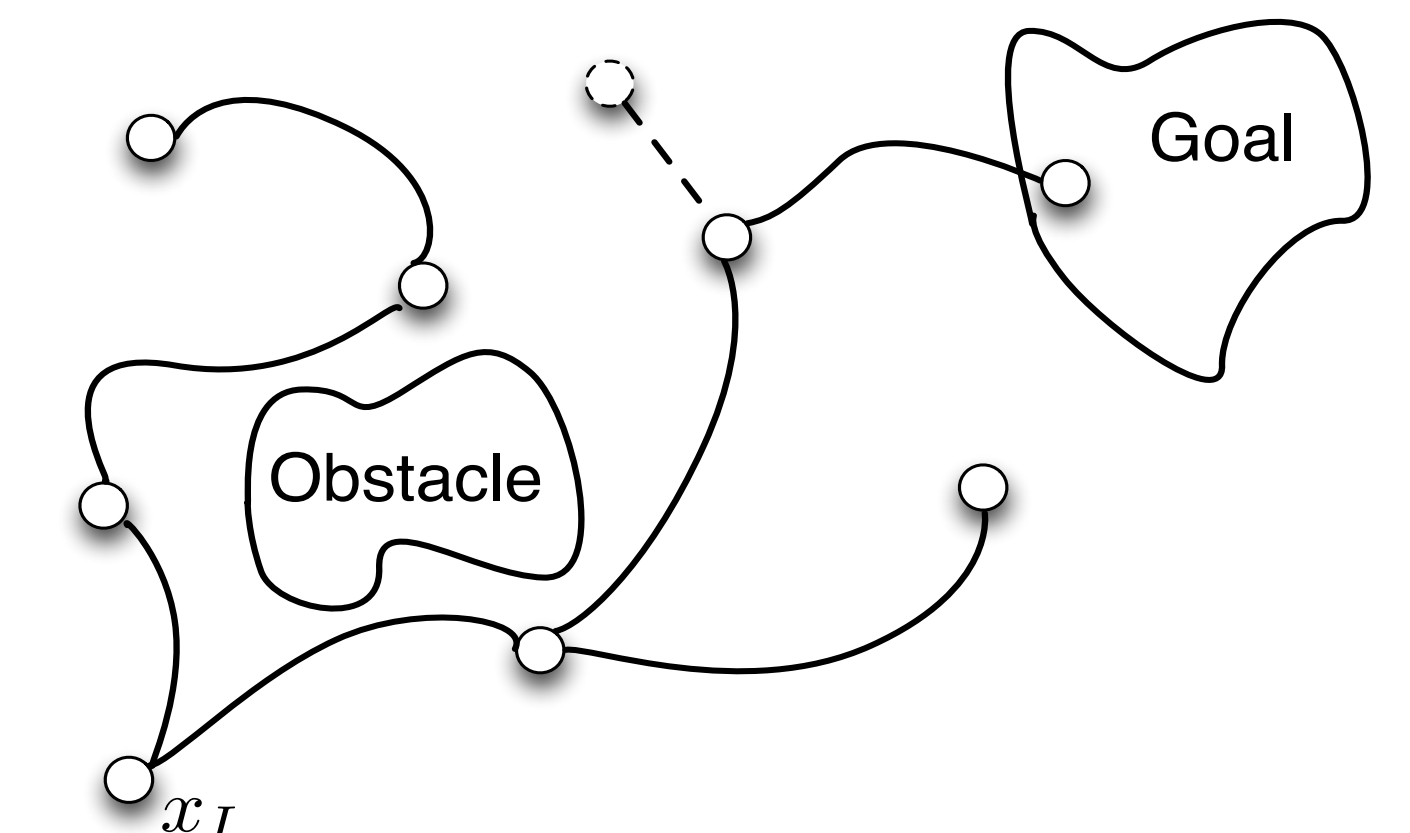 - **Pillar 3**: implementation and performance assessment

Figure 2: Rapidly exploring dense trees (RDTs) incrementally construct a tree of feasible trajectories in a way that quickly reduces the expected distance of a randomly-chosen point to the tree (x_I: initial condition).
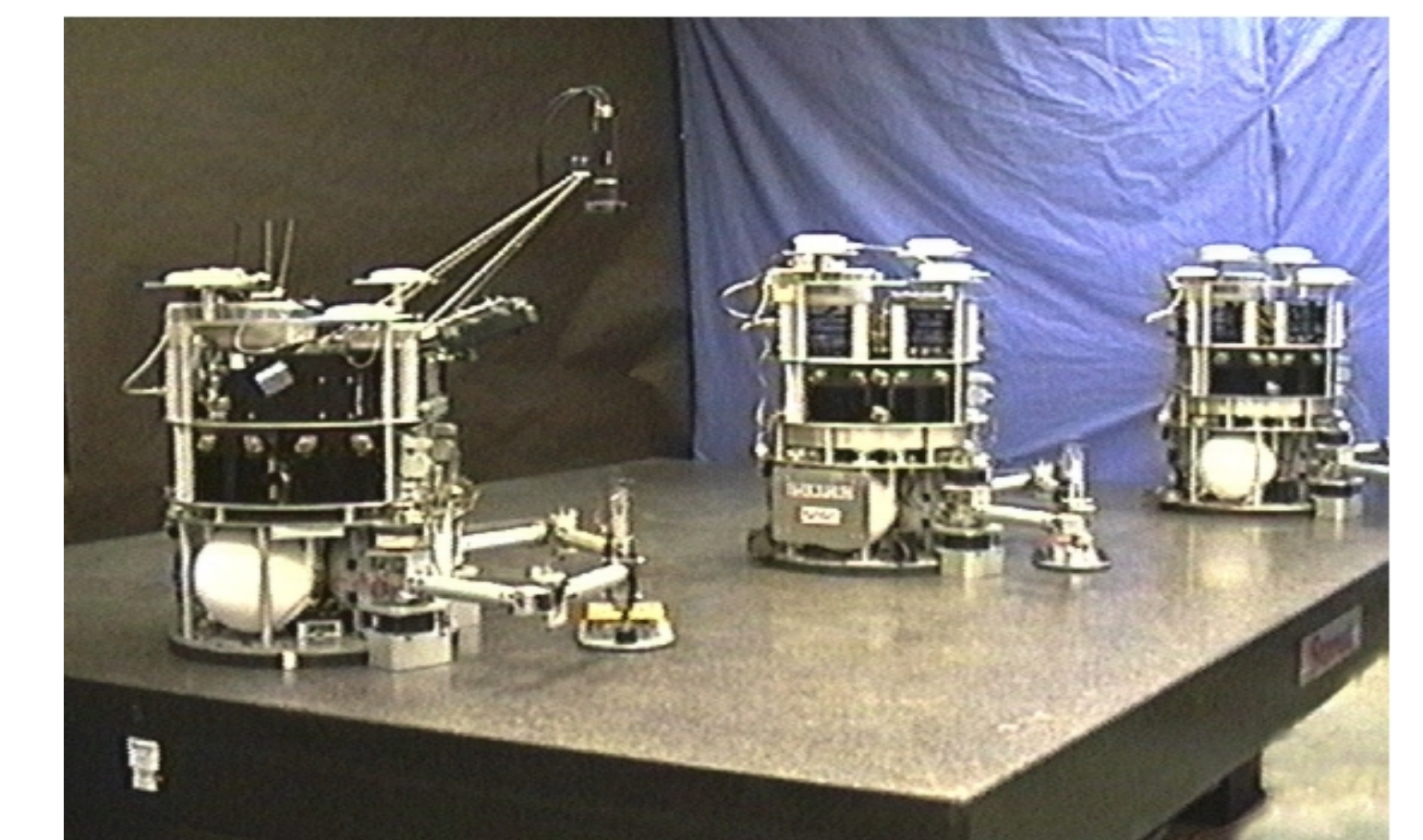
Method:

- Formal verification: rigorous analysis and synthesis tools to ensure the correctness of the design

- Experimental testbed: validation at the Stanford's space robotics facility

- Collaboration with JPL: instrumental to a possible technology infusion in future NASA missions

Figure 3: Stanford's space robotics facility

Challenges: Radical departure from traditional approaches, spacecraft maneuvering is a planning problem with unique features

Management plan

- PI: Dr. Marco Pavone, Assistant Professor at Stanford, Research Affiliate of NASA JPL

- Team: two Stanford research assistants, two collaborators from NASA JPL

- Milestone at end of effort: two spacecraft (with spacecraft-like hardware) capable of performing complex coordination tasks (e.g., playing "Pong") amidst moving obstacles and with simulated anomalies for 1 hour without collisions

- Equipment: Stanford's space robotics facility, with re-designed avionics

- Maturation: from TRL 1-2 to TRL 3-4.